STUDY OF EM RESPONSES UNDER SHOCK IMPACT ON ROCK SAMPLES. II. FIELD EXPERIMENTS

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Abstract

The problem of the electromagnetic responses at mechanical shock impacts on rock samples of various structure and composition is studied experimentally. This part is a logical prolongation of previous laboratory investigations described in Part I, and presents the results of field investigations on studying the structure of EM emissions generated by shock and explosive (low power) impacts on large monolithic blocks of rocks of complex structure in the ULF and VLF frequency ranges with use of the field experimental complex specially developed. The mechanisms of excitation of seismic emission (for various sources) and the generation of the EM response at propagation of seismic wave through a mechanical system, in particular rocks, are considered. The fact of generation of the EM responses at impacts on various wide-spread quartz-containing rocks was confirmed; it has been established that the source of the EM emission in the ELF-VLF range are the inclusions of a crystalline piezoelectric excited by seismic wave.

The existence of low and high-frequency parts of the response in the lower part of the VLF range of EM emission generated by impact, and the arising of modal structures in the high-frequency responses at impact to rocks in real conditions were detected. The proportionality of the piezoelectric response to seismic one, and an increase of the response amplitude due to the presence of an additional massive piezoelectric excited by means of a seismic wave are shown. No noticeable role of the structural destruction of the rock samples in the generation of responses was found, that gives a chance to their detection not only under hard impact (mechanical shocks, explosions), but al-so during natural seismic processes, that opens the perspectives for using the methods of prediction of seismic phenomena using the EM precursors of the earthquakes.

The results obtained are in good agreement with our results obtained earlier in laboratory experiments and presented in Part I of this work. They are an intermediate stage between laboratory research and the registration of EM responses at powerful industrial explosions. A description of the results obtained when studying the structure of EM emissions caused by strong impacts at industrial explosions will be presented in the next part of the work.

1. Introduction

Study of seismo-electromagnetic effects associated with the generation of electromagnetic (EM) signals at arising, as a result of seismic events, stresses leading to destruction of various rocks, is important, first of all, from the point of view of modeling of processes which occur in medium at the stage of earthquake preparation and at its initial stage. Such investigations can contribute to a better understanding of the physics of the earthquake's process, and they are necessary, in particular, for constructing an adequate model of seismic event, that is the basic element of any possible forecast system.

One of the main approaches in conducting such investigations is the study of EM responses under mechanical impacts and the destruction of rock samples in the experiments of various kinds. Earlier, in Part I of this work, we presented the results of laboratory experiments on the mechanical impact on rock samples. Here we present the results on study of the EM emissions arising as a result of shock and explosive (of low power) impacts onto large monolithic blocks of the rocks of complex structure, that is a natural development of the previous investigations in the laboratory experiments. Solving this problem, we have conducted the special nature field experiments away from sources of industrial interferences.

Note that conducting field experiments is an intermediate stage of research between laboratory experiments and the registration of EM responses of rocks at powerful industrial explosions. The need of such investigations is due to the following. At industrial explosions, the magnitude of the mechanical impulse generating the seismic (shock) wave has the order of $\sim 10^5$ $kg \cdot ms^{-1}$ (by one ton of explosive); in laboratory experiments, the magnitude of the similar impulse is approximately ~ 1 $kg \cdot ms^{-1}$ (mass of falling body, m=0.1 kg, the fall height h=0.5 m), thus the magnitude of the seismogenic factor in these processes differs by approximately five orders. In addition, in laboratory experiments, EM emission sources are rock samples with sizes of the several centimeters, and at industrial explosions, these sources will be geological objects with spatial sizes of hundreds of meters, i.e. the difference in sizes is also 4-5 orders.

Earlier, in [1-3] only preliminary results on the interpretation of experimental data obtained in field experiments, that do not satisfy the criteria of statistical significance were published. More detailed analysis and more strong interpretation of these and new results can be the basis for establishing the relationship between the seismic and EM oscillations, and this, in its turn, becomes the key to understanding the physical processes caused by seismic events and will be useful for formation of the methodics of their forecasting.

Thus, this part of the work is devoted to the description of the results of our experiments on the study of the structure of EM emission generated by both shock and explosive (of low power) impacts onto large monolithic blocks of rock of complex structure.

A description of the results obtained when studying the structure of EM emissions caused by strong impacts at powerful industrial explosions will be presented in the next part of the work.

2. Methods and Equipment for Field Experiments

As the area of experimental field work the Magadan batholith was chosen, the location of the observation points was determined by the need to study the features of the generated EM signals from various types of rocks in the center of the batholith and on its endocontact (2nd Armansky pass[1]), in mountain valley and on the top of the hill (absolute altitude 705 m), depending on the forest cover and weather conditions, for the same types of rocks – to compare of EM responses at blown and explosive impacts.

For the field experiments, we used the specially constructed field measuring complex consisting of:

- electrical antennas;
- two identical receiving devices;
- piezoelectric seismic sensor;
- connecting coaxial cables;
- a powerful laptop computer with a sound card for digitizing signals;
- batteries for powering the equipment.

As antennas we used:

- an antenna of type "oblique beam" with a height of its suspension of 4 m, as the main device;
- a metal mast 4 m high as an additional auxiliary device to confirm the results.

The composition of the seismic sensor included a piezoelectric element and a differential amplifier with a gain of the order of 200, made on an operational amplifier.

The following sources of seismic signals were used to generate the EM emission in our field experiments:

a) hammer blows to the massive (usually granodiorite) monoliths with a sizes of 0.5–1 m;

b) impacts at free fall of stones weighing 20–30 kg from height of 1.5–2 m on rocky monoliths 2–5 m in size;

c) explosions of small powder charges of low power (10–15 g). The charges were located on the same basis to which blows were made, and were covered from above by heavy stones.

A piece of quartzite from the Natalka deposit (Magadan region) was used as a model of a quartz vein; it was located, as a rule, at a distance of about 1 m from the impact site. Sometimes, blows were applied directly over the surface of quartz.

3. Some Theoretical Estimates

The source of seismic emission can be an earthquake, explosion or shock impact, and according to the results of experiments [4], the physical characteristics of the seismic waves from these sources at the same momenta are identical.

In accordance with the concepts of seismic emission presented in [4], this process is described as the propagation of a mechanical pulse in a continuous medium. The pressure of seismic emission N affects the environment and causes the excitation of electrical signals from the inclusion of piezoelectrics. It is possible to easily calculate the pressure created by the impact of a freely falling body from the following expression [1, 4]:

$$N = M v_p \sqrt{2gh} / (4\pi R^2 L), \tag{1}$$

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[1] About 20 km from Magadan city.

where N is the pressure, $N{\cdot}\mathrm{m}^{-2}$, at distance R, m; M is the mass of the body, kg, freely falling from height h, m; L is the size of body, m; and v_p is the propagation velocity of seismic signal in the body material, ms^{-1}. When using (1), it should be taken in mind that the impact is hard, and the derivative of the momentum is replaced by the ratio of the momentum density to the time of the impact, i.e. it is assumed that the momentum is being completely transmitted to the medium during the wave propagation in the body material so that the wave packet has a duration $\tau = L / v_p$.

In explosions of chemical charges, pressure can be estimated from similar expression:

$$N = M v_d \sqrt{2K} / (4\pi R^2 L), \tag{2}$$

where M is the explosive charge mass, kg, with energy equivalent K, J·kg; L is the charge length, m; v_d is the explosive detonation velocity. The initial assumptions here are the same as in the previous case: the medium is assumed to be rigid, the impulse is formed into a packet of duration $\tau = L / v_d$ (detonation time τ determines the rise time of the first signal, i.e. 4τ is approximately equal to the period of the main oscillations T) .

In the experimental works [5], as the main source of seismic emission, the explosions of charges of ammonium 0.2 kg were considered. Such sources provided the receiving of the seismic signals from the depth of 60 m. In accordance with (2), it is possible to calculate the seismic pressure created by such explosion at the distance of 50 m:

$$N(50) = 0.2 \times 500 \sqrt{2 \times 4.6 \cdot 10^6} / (4\pi \times 50^2 \times 0.2) \cong 500 \ \mathrm{N \cdot m^{-2}},$$

$$\tau = 0.2 / 5000 = 4 \cdot 10^{-5}\mathrm{s}.$$

Thus, we assume that pressures of 500 $\mathrm{N{\cdot}m^{-2}}$ and more ensure the formation of electrical signals from inclusions of natural piezoelectrics.

In our field experiments, we used seismic signals excited by hammer blows weighing 1 kg, throwing off stones of 30 kg from the height of about 2 m, and explosions of charges of smoke powder weighing about 15 g. Let us estimate from expressions (1) and (2) the distances at which these sources provide pressures of more than 500 $\mathrm{N{\cdot}m^{-2}}$:

$$R_{\mathrm{blow}} = \left[M v_p \sqrt{2gh} / (4\pi L \cdot 500) \right]^{1/2}; \tag{3}$$

$$R_{\mathrm{expl}} = \left[M v_d \sqrt{2K} / (4\pi L \cdot 500) \right]^{1/2}. \tag{4}$$

So, we obtain from formulae (3) and (4) for used sources:

a) blow by hammer falling from the height of 5 m (muscular effort was added to the free fall): $R_{\mathrm{blow}} \approx 7.5\,\mathrm{m}$; hammer blows created pressures above 500 $\mathrm{N{\cdot}m^{-2}}$ at a distance up to 7.5 m; $\tau \cong 3 \cdot 10^{-5}\mathrm{s}$;

b) impact of a stone weighing 30 kg, freely falling from a height of 2 m: $R_{\mathrm{blow}} \approx 17.3\,\mathrm{m}; \tau \cong 10^{-4}\,\mathrm{s}$;

c) impact of a stone weighing 7 kg, freely falling from a height of 10 m: $R_{\text{blow}} \approx 12.5\,\text{m}$; $\tau \cong 10^{-4}\,\text{s}$;

d) explosion of a charge of 15 g of smoke powder (K = 2.5×10^6 J·kg^{-1}; v_d = 3000 ms^{-1}): $R_{\text{expl}} \approx 7.3\,\text{m}$; $\tau \cong 2 \cdot 10^{-5}\,\text{s}$.

The estimates obtained allow us to conclude that, during field experiments, seismic radiation sources created pressures (causing EM responses) of more than 500 N/m at distances of at least 9 m, and the main frequencies of seismic oscillations were about 1-10 kHz.

4. Field Experiments

In our experiments, EM responses were observed for all types of shock and explosive (for low power explosions) impacts. Consider and analyze some examples of the results.

Figure 1 shows a spectrogram of recording responses at throw off of the stone (granite) weighing 25-30 kg from the height of about 1.5 m onto a large granite monolith recessed into fine rocky soil (the measurements place is the Gornyak quarry[2]). The intensity of the responses is displayed by the color in accordance with the lower color scale, the gray color corresponds to the lack of response in the analyzed amplitude range.

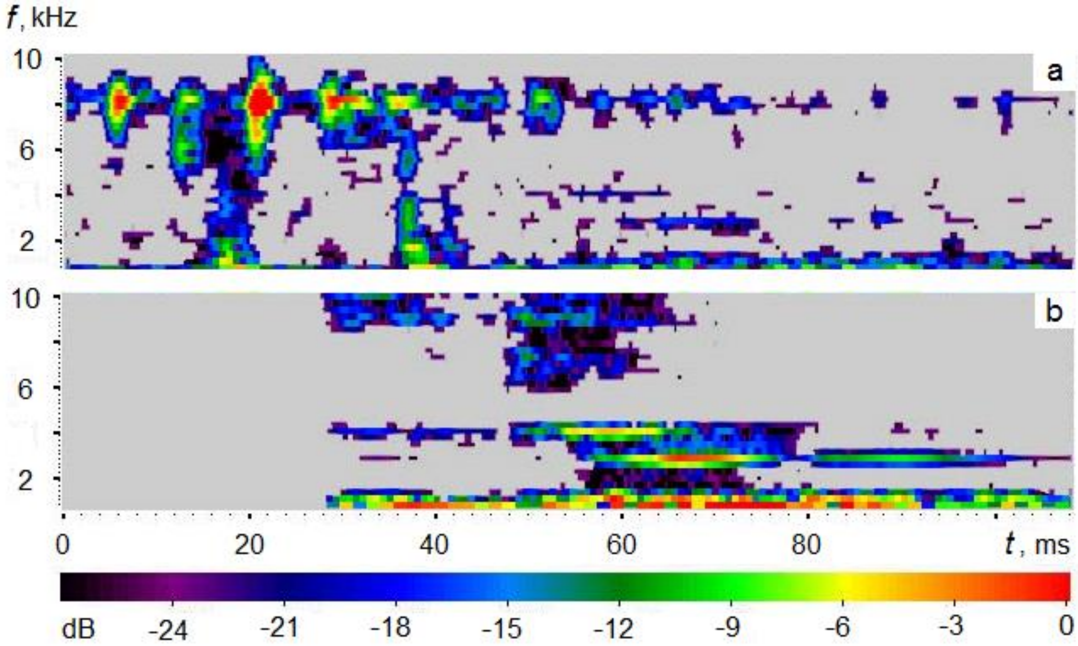

Fig. 1. Electrical and seismic responses at a stone throw off from the height of about 1.5 m: a – electrical signal, b – seismic signal.

In the experiment, the antenna with the receiver was located at 5.5 m, and the seismic sensor was 3 m from the sample. At a time of ~ 17 ms (in current time coordinates), a response from the impact in the upper spectrogram (electrical signal) is observed. The

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[2] Near the Magadan city.

seismic signal starts from 28 ms. At time 36 ms, one can see the response from the action of the seismic wave to the receiving complex in the spectrogram. Figure 2 shows a record of the corresponding temporal realizations (the signal amplitude is indicated in units of the least significant bit of the ADC). Here, the response signal is masked by the atmospherics recorded in the same frequency band, and the response is identified less clearly.

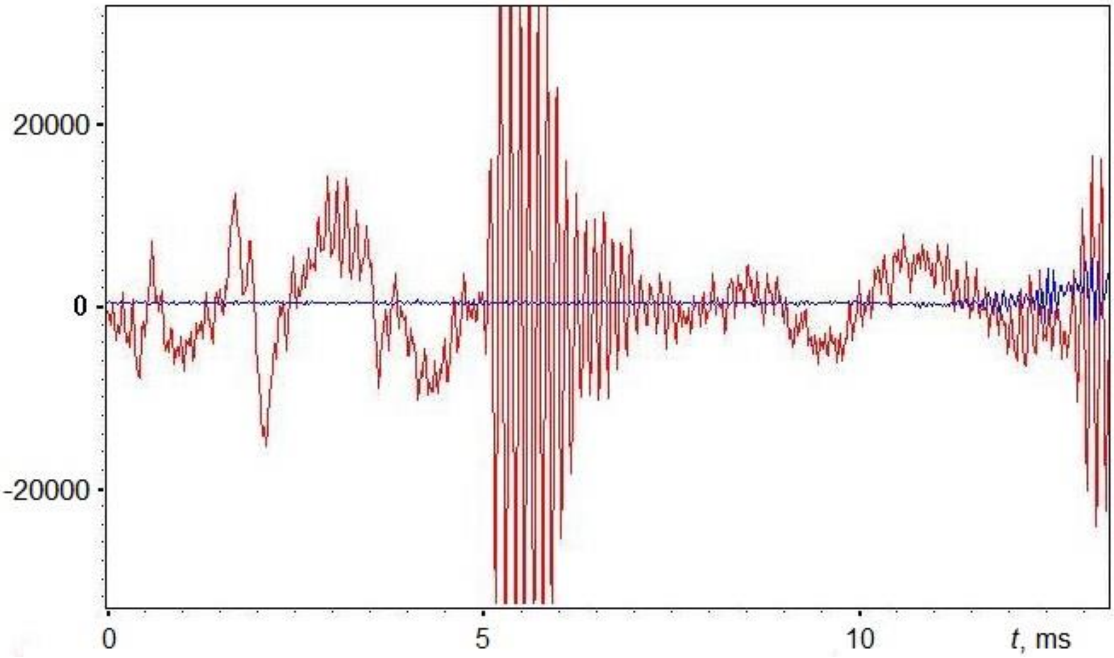

Fig. 2. Oscillograms of the electrical (red line) and seismic (blue line) responses corresponding to the spectra shown in Fig. 1.

Figure 3 shows spectrograms for four blows by geological hammer to the stone used in the previous experiment. The responses from the 3rd and 4th blows are most clearly visible. For them, as in Fig. 1, the low-frequency and high-frequency (at about 4 kHz) parts are visible. The response from the second blow coincides with the signal of the atmospherics and identification of the response in high-frequency part is difficult. At the first blow, there is only a low-frequency response, the seismic signal for this impact is visually weaker. It is possible that the impact was weaker, and it is also possible that a significant part of the impact energy was expended for the destruction of the sample and elastic oscillations in the sample were not excited. In this case, the assumption coincides with that made when analyzing the data of laboratory experiments (see Part I of the paper).

Figure 4 shows the temporal records for the 3rd blow. One can see that the response is weaker than at throw off of a stone, however, not proportionally. It should be noted here that in this experiment the stone has fell its plane and the effect was quite long in time. Therefore, further consider other results, where the stone impacts the monolith by its edge. Figures 5 and 6 show the spectrograms and oscillograms for three blows. For the last two, the fall height was increased by 0.5 m.

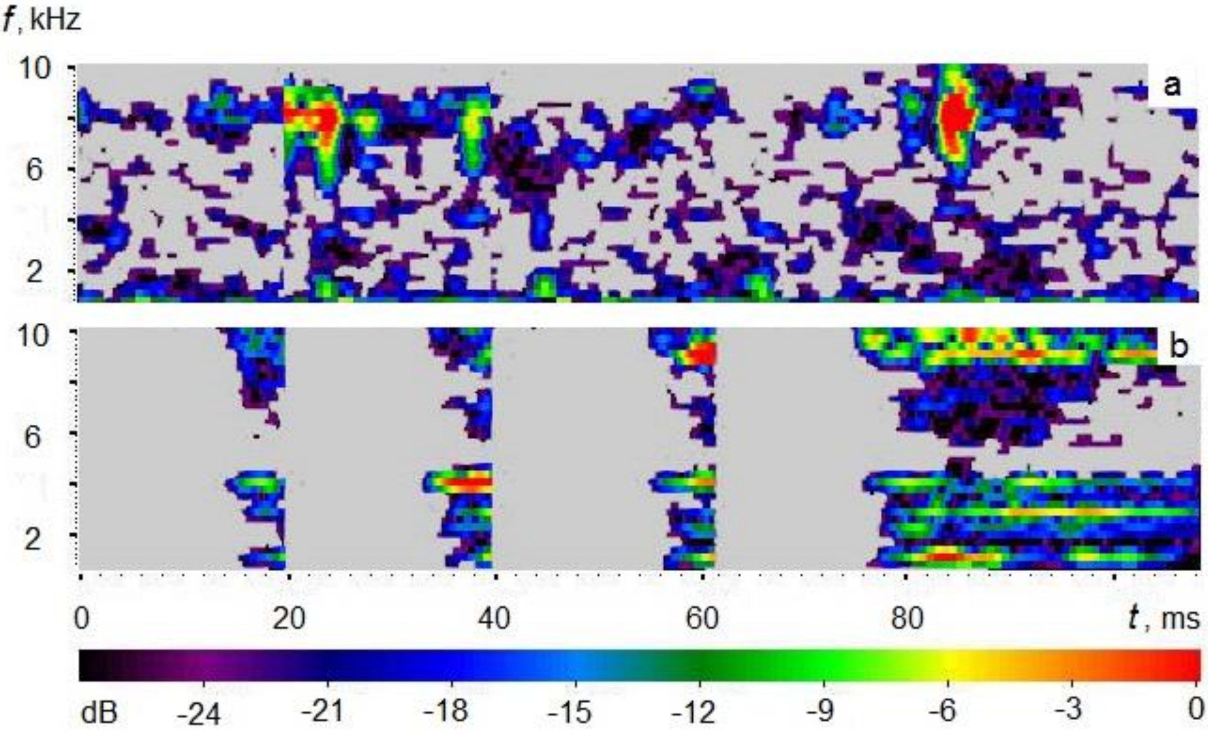

Fig. 3. The electrical (a) and seismic (b) responses from the four blows by the geological hammer to the same stone that in Fig. 1.

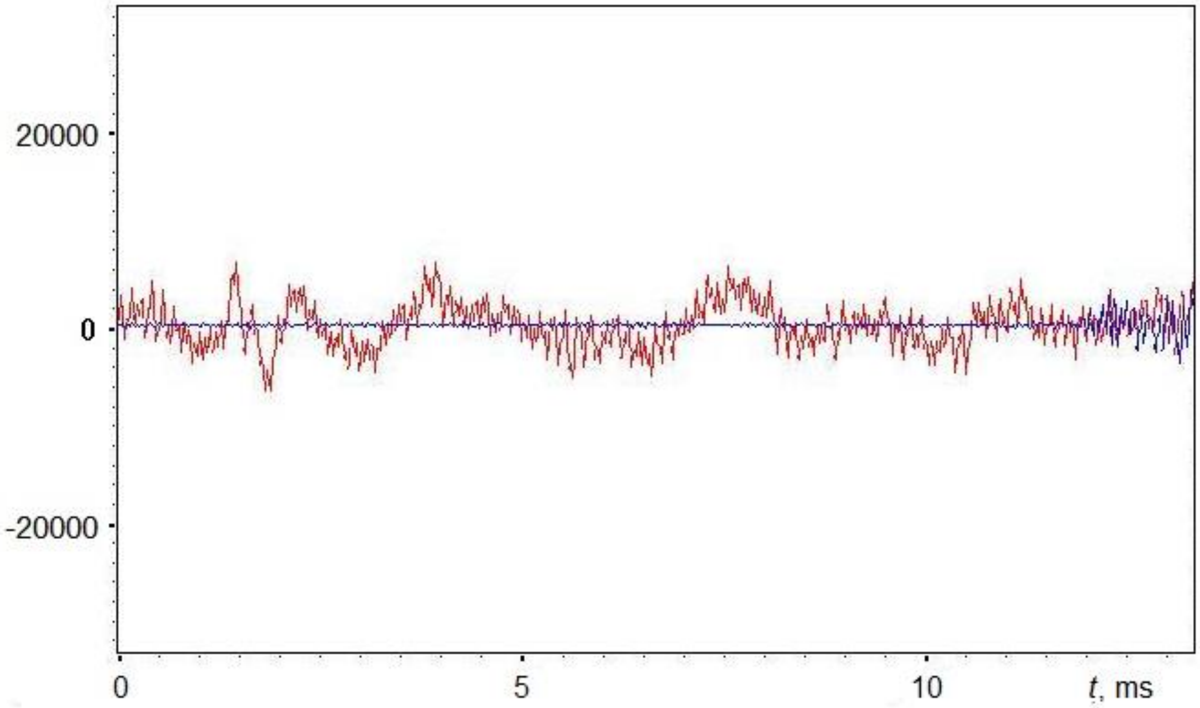

Fig. 4. Oscillograms of the electrical (red line) and seismic (blue line) response from a 3rd, shown in Fig. 3, blow by the geological hammer.

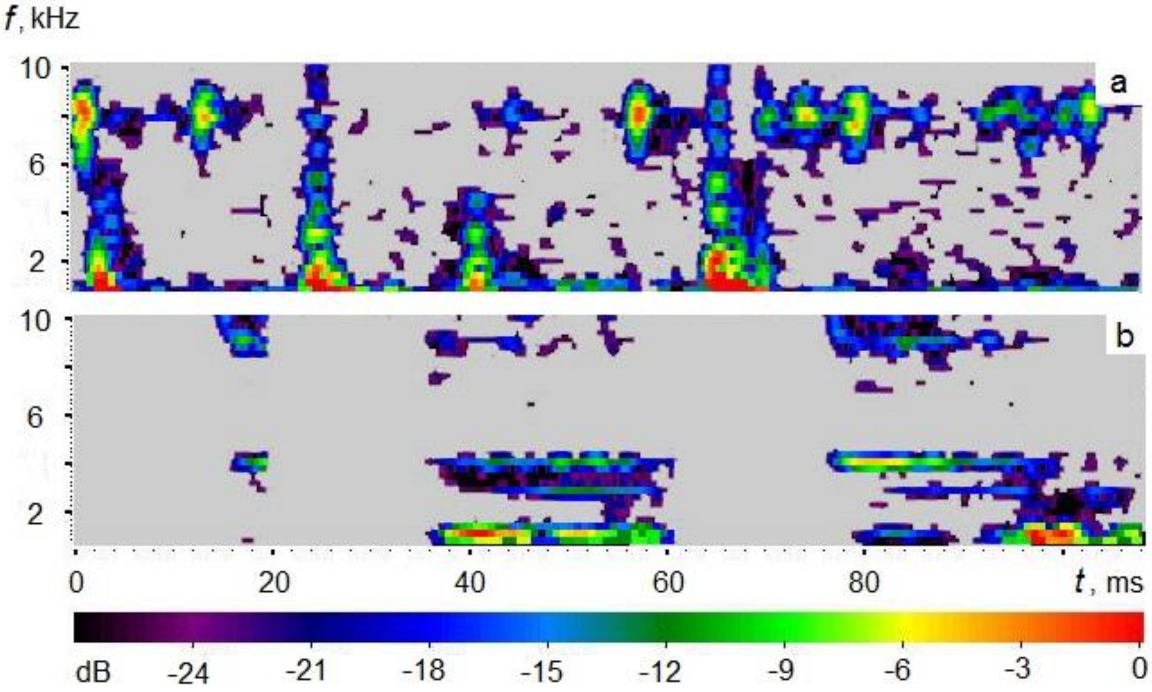

Fig. 5. The electrical (a) and seismic (b) responses at three blows by a stone:
1st blow corresponds to the fall height of about 1.5 m, 2nd and
3rd blows – to fall height of about 2 m.

The response feature in Fig. 5 is the blur of the high frequency part. For the 2nd and 3rd impacts, the reason for this is the signal limitation observed in Fig. 6. But for the first impact, there is no such limitations and a possible cause may be the excitation of several types of mechanical oscillations upon impact. The last two impacts also have a certain stability of temporal forms, although the identity is distorted due to the limitation of signals. Steep leading fronts and damping on the rear ones can be a consequence of the special nature of the excited mechanical oscillations. Compared to the responses at hammering, a significant increase in signals is observed, as expected. There is also a certain oddity for the first impact, expressed in the absence of the low-frequency part of the seismic signal in Fig. 5. In fact, this part appears on the spectrogram, but with a delay of 45 ms comparatively the high-frequency one, the reason for which, however, is not yet clear.

In laboratory and field experiments, we observe the EM field at distances much shorter than the wavelength, i.e. in the near zone of the source [6]. The electric field of the dipole in the near zone weakens inversely with the cube of the distance. Therefore, we consider the responses from a stone blow at a distance of 2 m from the antenna (2.5 m from the seismic sensor). Figure 7 shows the spectrograms of five blows with a bench hammer (with use of the geological hammer there was a limitation of responses that were approximately twice large in amplitude[3]), and Figure 8 shows the impulses of electrical responses for the 1st, 3rd and 4th blows (time intervals 0-5, 5-10 and from 10 ms).

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[3] The response amplitude was of the order of 30,000 units of the low binary digit of the ADC compared to 60,000 units for the geological hammer.

Comparison of the results obtained in experiments at different distances of the antenna from the place of impact allows us to conclude that we actually register a real electrical signal from the impact, and not from any other effect.

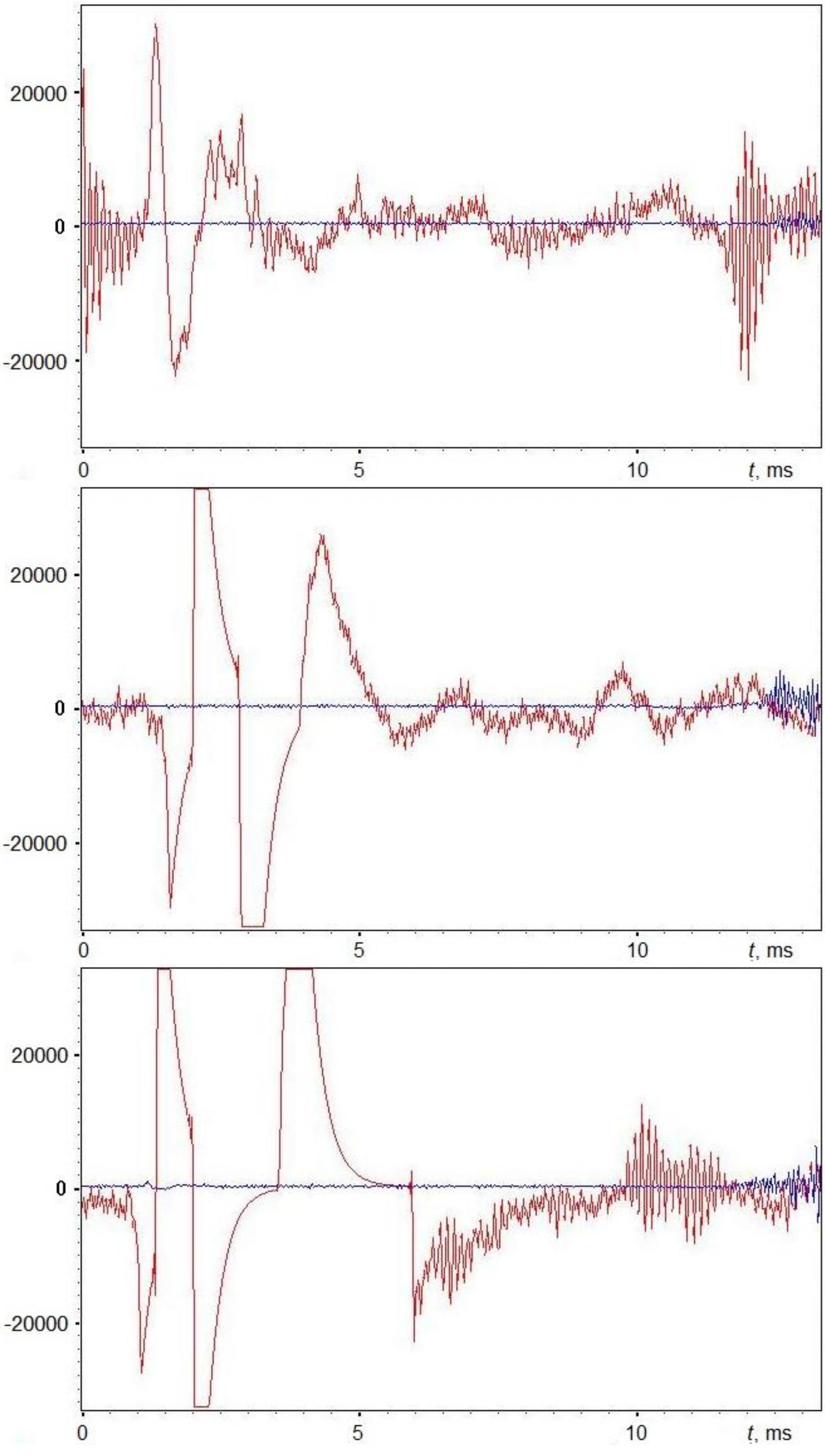

Fig. 6. Oscillograms of the electrical (red line) and seismic (blue line) responses at three blows by a stone corresponding to shown in Fig. 5.

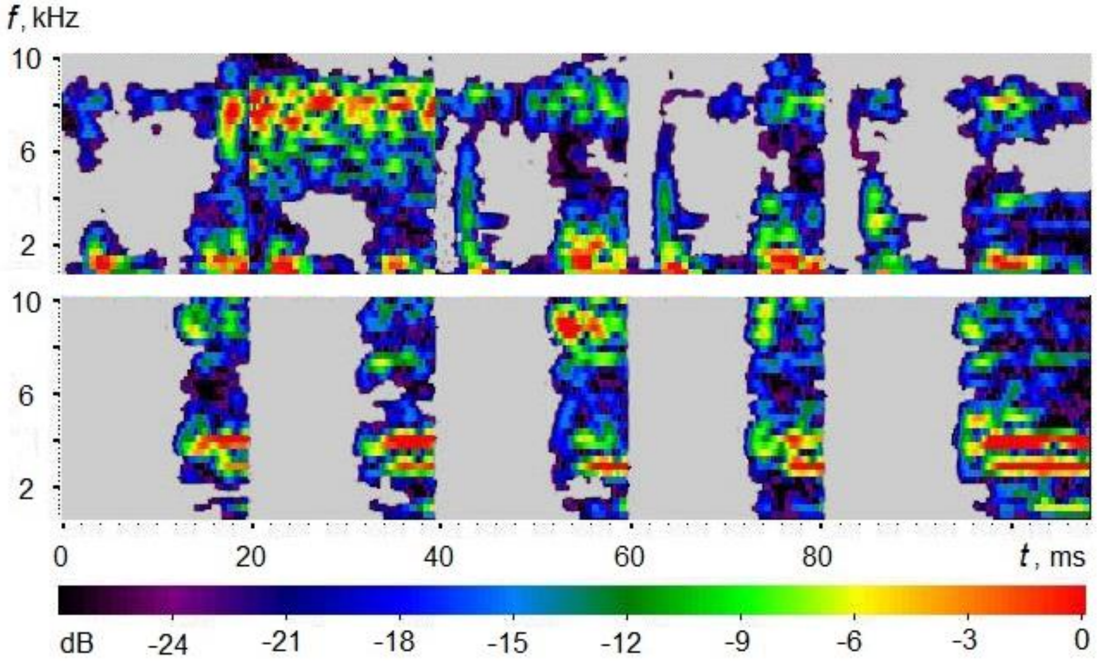

Fig. 7. Responses at blows by the bench hammer to the granite sample located close to the antenna.

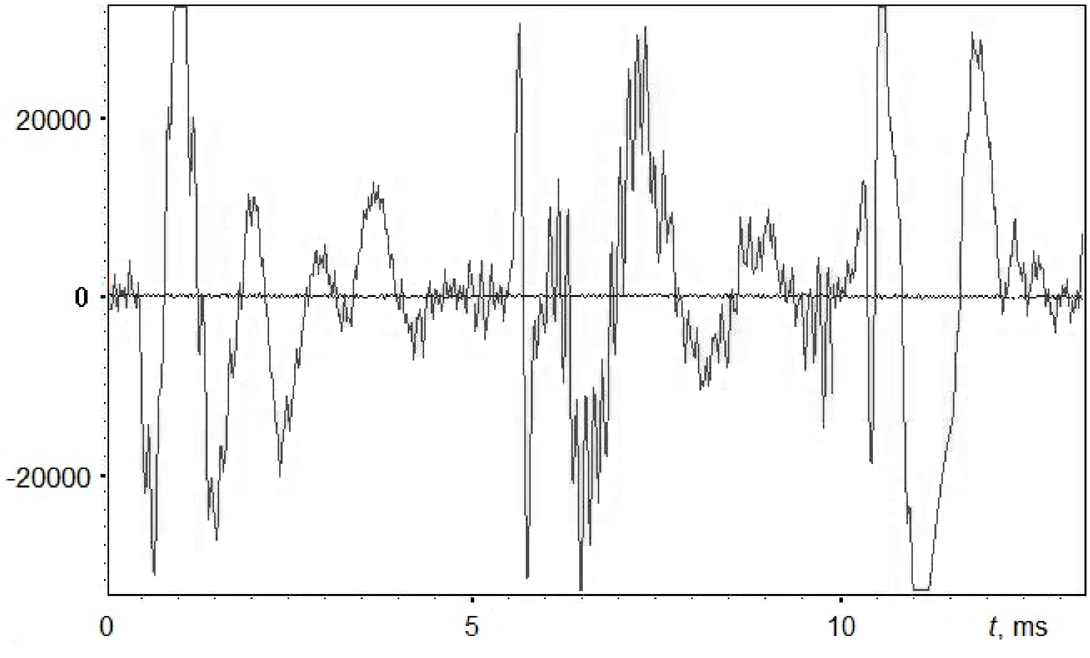

Fig. 8. Oscillograms of the electrical responses at blows by the bench hammer to the granite sample located close to the antenna.

If we compare the responses in Fig. 8, we see that they have a different temporal structure. However, according to Fig. 7 they have common features. The 1st, 2nd and 4th responses have a distinct low-frequency part, while the 3rd-5th ones have a high-frequency part with spectral maxima at 3 and 4 kHz. Since the response frequencies are of the same order as at blow to a distant stone (see Figs. 1 and 3), but the stones have different sizes and configurations, that the frequency-forming factor is not the standing seismic wave that could be excited in the sample, but it is a passage of the wave in a sample. It is possible that the frequencies are determined by the propagation velocities of the modes of seismic waves excited in the sample, and possibly also directly by its structure and composition. In both cases, the premises for using the responses from seismic impacts for diagnostic purposes appear. To confirm these assumptions, additional laboratory experiments with samples of different compositions using the registration of seismic waves in the sample are necessary. As to the ratio of low and high frequency responses, we think that it is defined by ration of the inelastic and elastic deformations of the sample.

Figure 9 shows spectrograms for the case of a blow of the granite sample weighing 6-7 kg thrown off from the height of 7 m onto a granite monolith at a distance of 10 m from the antenna. Figure 9 shows spectrograms for the case of a blow of the granite sample weighing 6-7 kg thrown off from the height of 7 m onto a granite monolith at a distance of 10 m from the antenna. One can see two responses (from one impact) occurring after a few milliseconds. Further, at the impacts the falling sample was fell apart onto pieces and the next three responses can be explained by impacts of fragments (see oscillogram in Fig. 10).

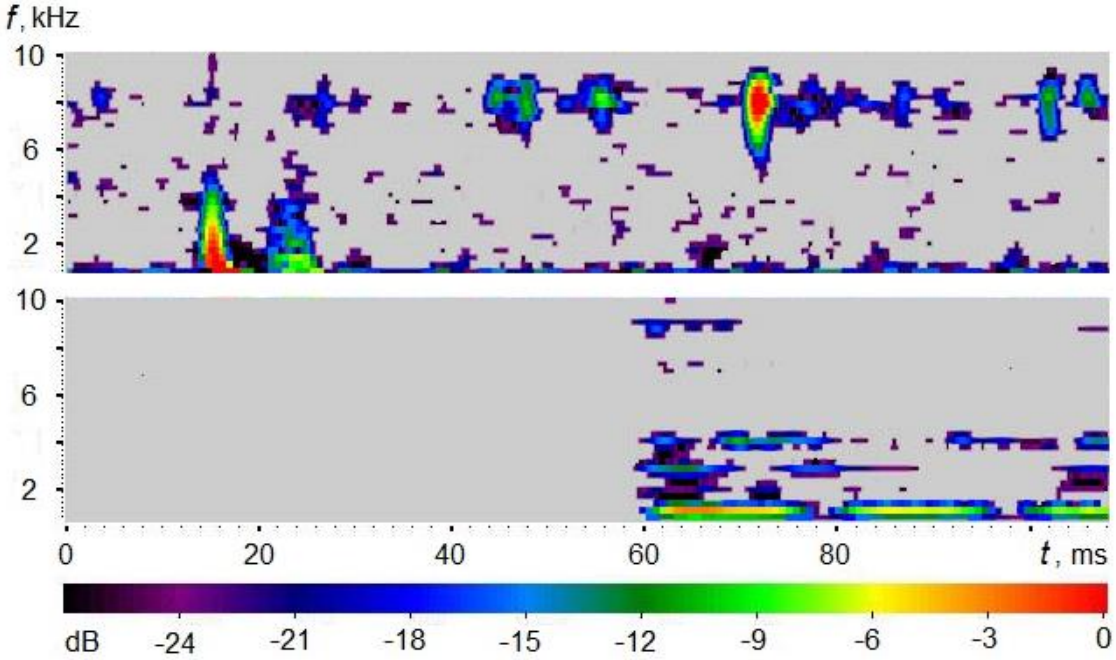

Fig. 9. An example of the responses at a granite stone throw off from the height of about 7 m to granite monolith.

Figure 11 shows the combined spectra for another 5 impacts responses, and Fig. 12 shows the oscillograms of the first two blows corresponding to Fig. 11.

A feature of the oscillograms shown in Figs. 10 and 12 is a repeating form of pulses. A similar character of the responses occurs also for other impact cases given in Fig. 11. Impacts correspond to the samples used for throwing: 1 and 4 – to full-crystalline granite, 2 and 5 – to granodiorite and 3 – to dark-colored rock with a minimum amount of quartz. This indicates that the response is observed from the main sample, to which the blow is produced, and not from the thrown off stone.

In the first 3 blows in Fig. 11, a distinct high-frequency part of the responses is visible, and in the last two ones it is much weaker. This is because, firstly, as can be seen in Fig. 12, a slight signal limitation is observed in the first blows, while for the last two it is absent. The limitation is manifested in the appearance of a response at frequencies above 6 kHz. The response at frequencies of 3–5 kHz is present in all spectrograms, but individual spectral components are absent or poorly noticeable in it. Most likely this is due to the redistribution of the contribution from the mechanisms of elastic and inelastic deformations towards the latter under stronger impacts. This part of the signal masks weaker signals from the wave of elastic strains. In this regard, the response from natural seismic impacts on rock masses may be more informative. Of course, if this response can be distinguished against the background of atmospheric interferences.

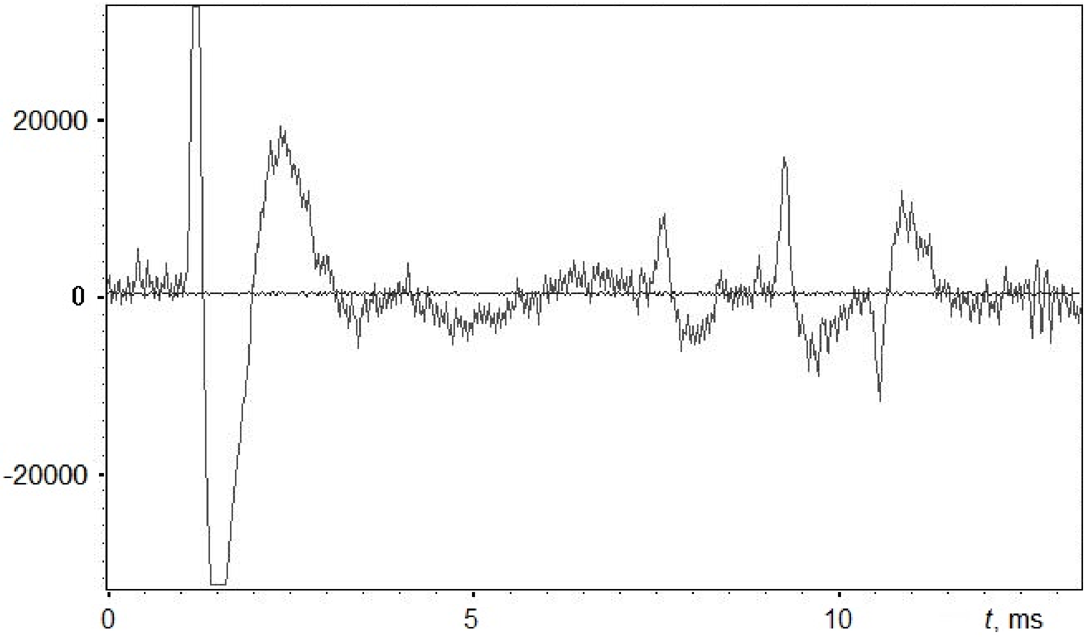

Fig. 10. Oscillogram corresponding to Fig. 9.

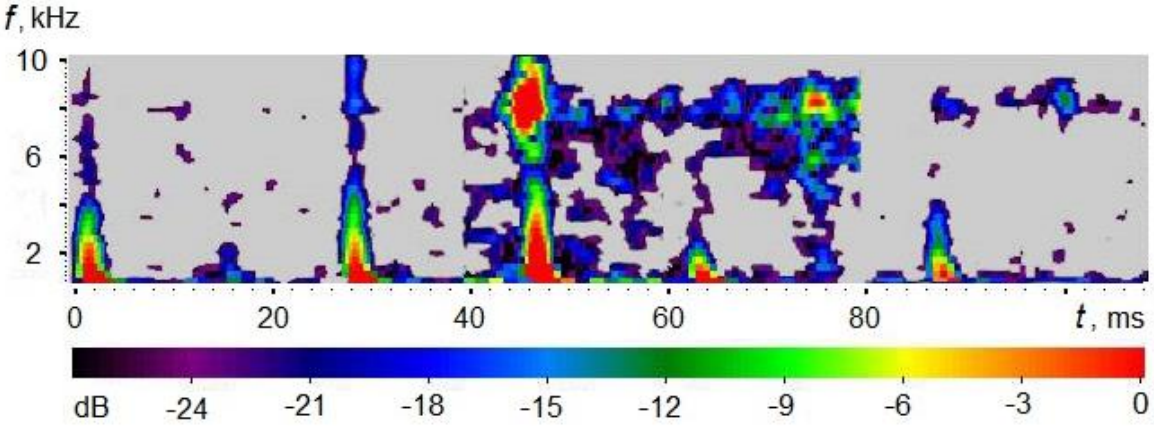

Fig. 11. Spectrogram of five impacts by a granite stone on granite monolith from the height of about 7 m (electrical response).

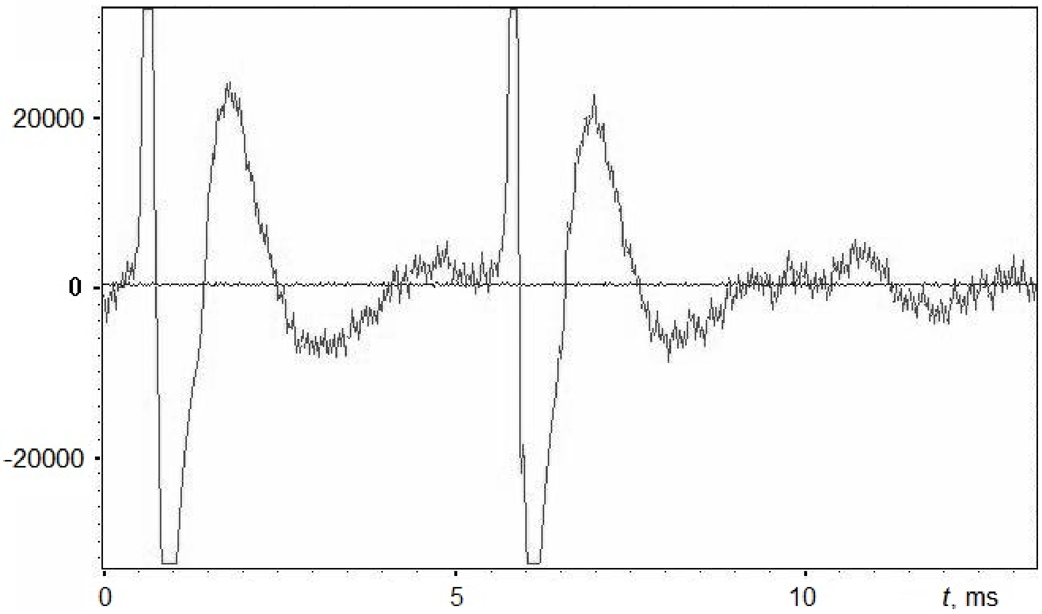

Fig. 12. Oscillogram of the first two impacts corresponding Fig. 11.

Figure 13 shows the spectrograms of responses from four low-power explosions conducted on a stone 5 m from the antenna, and Fig. 14 presents an oscillogram of one of them (the second), where there are fewer signal limitations. An explosive charge was covered from above by a stone. In general, responses are similar to those observed at blows.

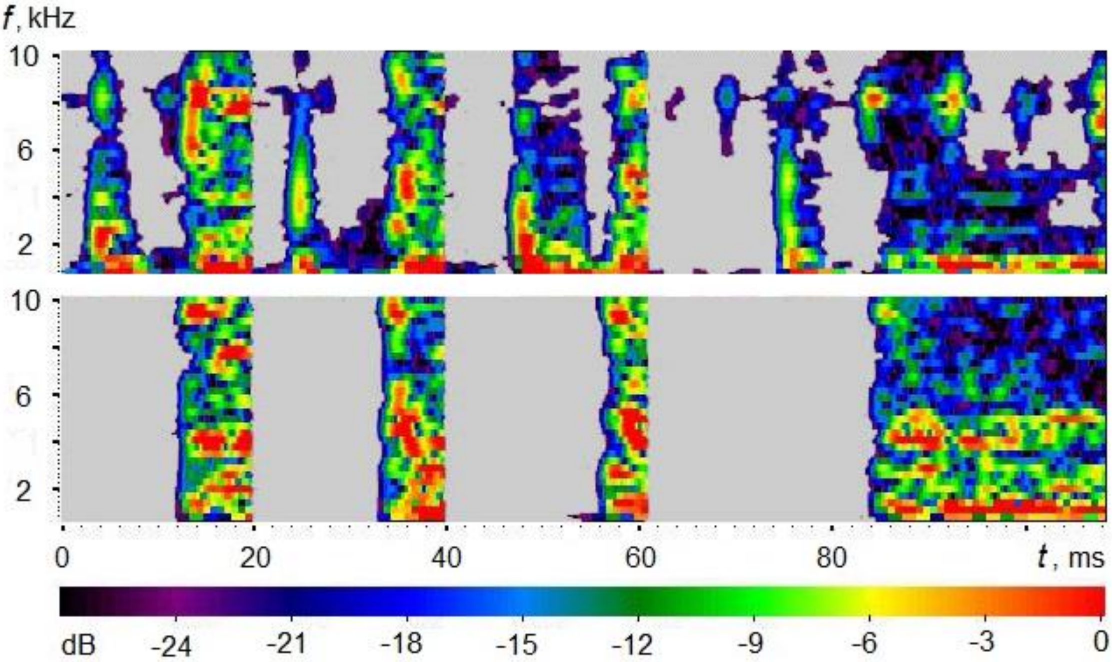

Fig. 13. Spectrograms of the responses of the four low power explosions.

In experiments, destruction of samples was often observed. In this regard, the question of the contribution of the effect of macro-destruction to signal arises. Figures 15 and 16 show the responses from impacts on a diorite sample by a bench hammer 2.5 m from the antenna. In the second case, a quartz sample is placed on the stone. During the blows, the pieces were broken off from a sample of diorite. The experiment was conducted at the 2nd Armansky pass at the edge of the forest in a mountain valley.

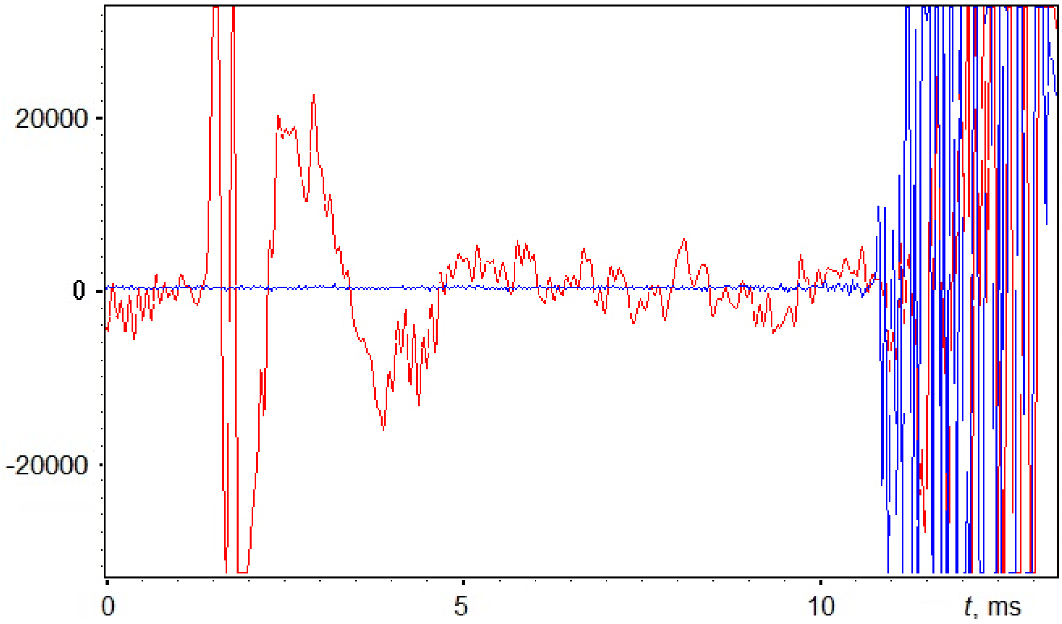

Fig. 14. Oscillogram of the response of the 2nd explosion in Fig. 13.

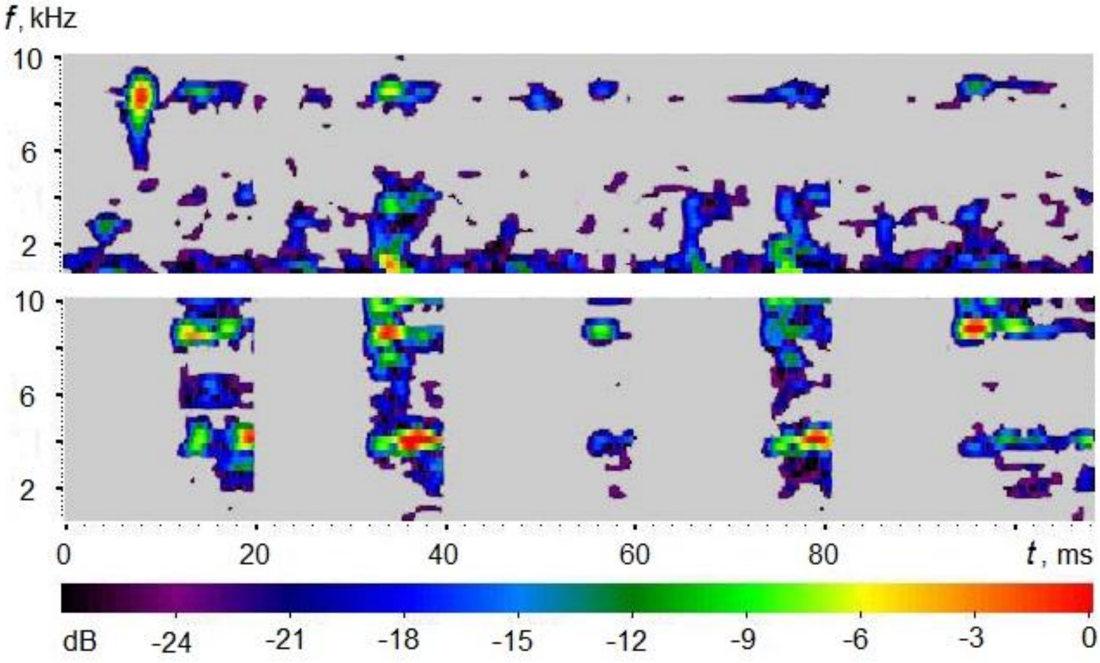

Fig. 15. Response spectra from hammer blows on a diorite sample
at a distance of 2.5 m from the antenna.

The responses at blows to a unit sample are weak and amplified by the addition of quartz. Besides, one can visually notice a tendency that a weaker electrical response corresponds to a weaker seismic one. It can be assumed that the seismic response is weakened if part of the impact energy is spent for the destruction of the sample and, accordingly, the energy of the seismic wave causing the electrical response decreases. To test this hypothesis, mathematical processing of the experimental data was carried out, and the energies of the electrical response and of initial part (20 ms) of the seismic one were calculated.

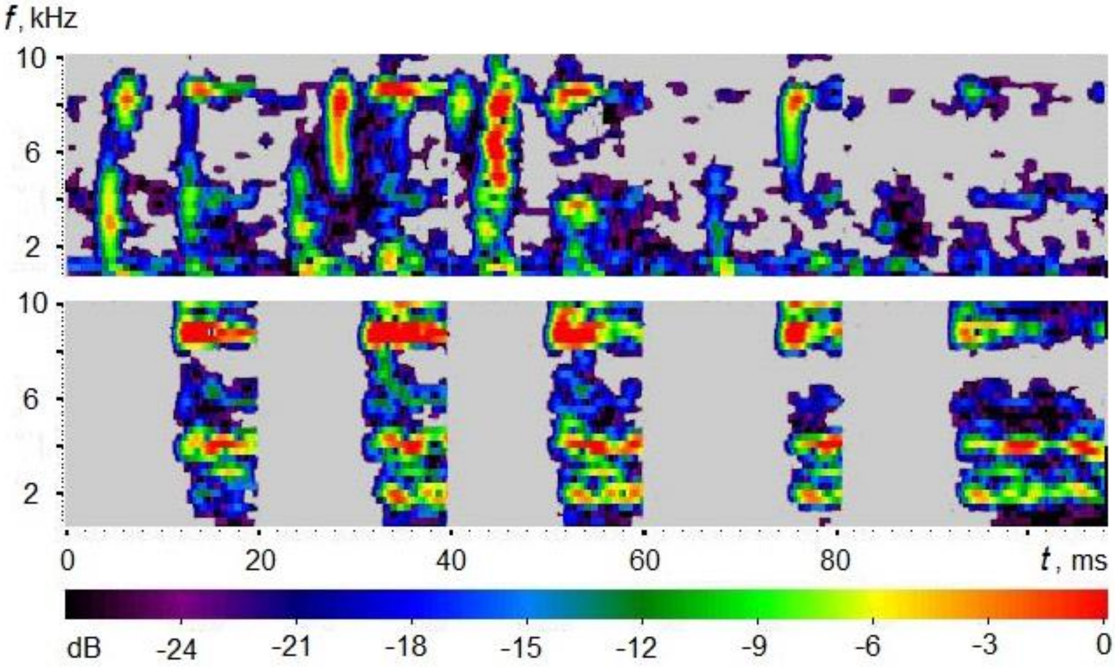

Fig. 16. The same as in Fig. 15 but for the diorite sample with a piece of quartz.

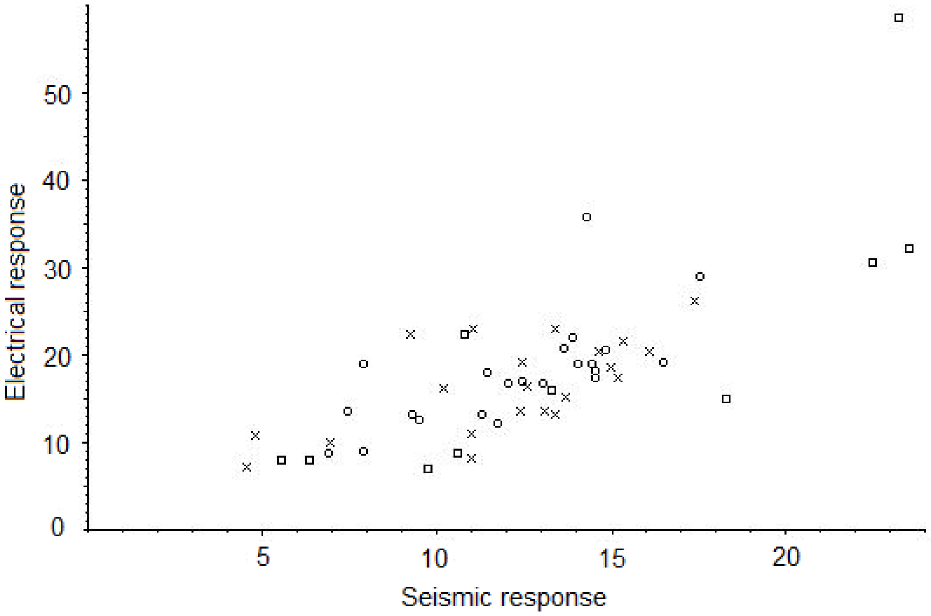

Fig. 17. Dependence of the effective amplitude of the electric signal on the seismic response.

Figure 17 shows the dependence of the effective amplitude of the electric response on the effective amplitude of the seismic one (in relative units). The experimental points for the diorite sample are marked by crosses, and the points for diorite with the superimposed quartz sample are marked by circles. The results of the experiment on the destruction of a granite sample, which was carried out in a lowland behind the lake, are plotted by squares. Note that the point with the maximum energy of the electric response corresponds to the first blow made with less force, so as not to cause destruction of the sample. In Fig. 17, on average, the proportional dependence is clearly visible, that confirms our hypothesis that the most of the EM emission is generated by the seismic wave, and if the macro-fractures give a response, that its amplitude is much lower.

In addition, we carried out field measurements under other conditions different from the conditions of previous field experiments at the base point of measurements, namely: on a mountain pass[4] near a forest in a narrow mountain valley, and on a plain near a large lake in conditions of a wet ground.

In the first case, the conditions determined the decrease of the level of emission of atmospheric origin, while, however, the efficiency of the receiving antenna also decreased. Nevertheless, we were able to obtain results that are interesting, inter alia, in terms of comparing them with the results obtained earlier at the base measurement point. Figure 18 shows the spectrograms of responses for blows on granite monolith by a stone (0–20 ms), by bench hammer (20–40 ms), by hammer on a quartz sample mounted on the granite monolith (40–60 ms) and by hammer on quartz (60–80 ms and from 80 ms).

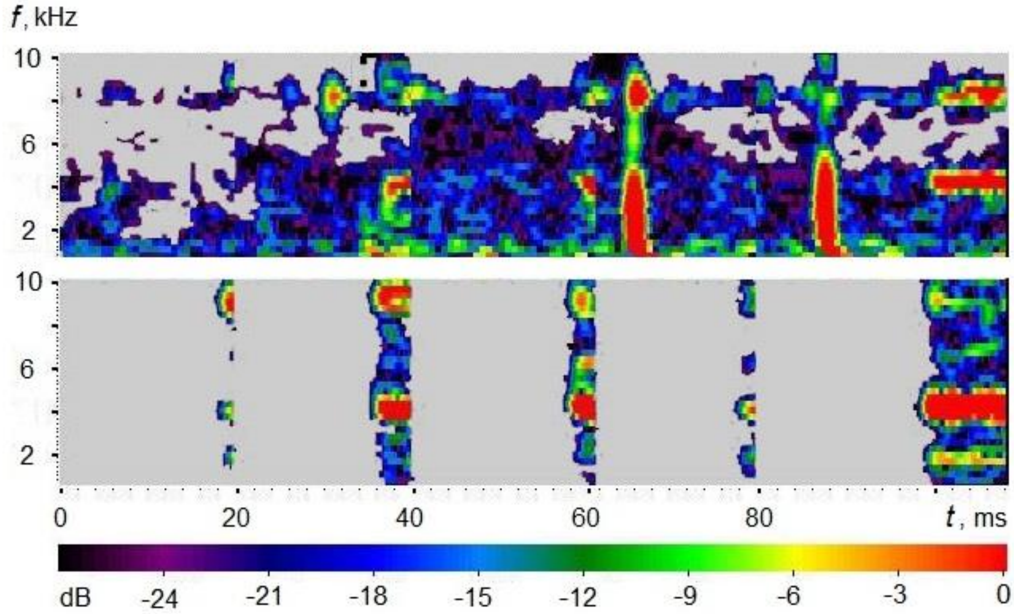

Fig. 18. The electrical and seismic responses observed in the experiments on the mountain pass near the forest in a narrow mountain valley.

One can see that in the first two cases the responses, although small, are distinguishable against the background of weak atmospheric noise, but in the third case they are difficult to distinguish on the noise background. But, at the blows on quartz, the response is very strong. In addition, if to consider the case of impact on a granite stone with quartz taking into account the response from only quartz, a certain similarity is

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[4] 2nd Armansky pass.

found in the low-frequency region and the response from the impact of a seismic wave on quartz through a stone is observed. A characteristic feature of quartz responses is the presence of a high-frequency part at frequencies above 6 kHz, that corresponds to the damped oscillations following after the main pulse. Fig. 19 shows as an example the oscillogram of the last response in spectrum shown in Fig. 18. Note, that for the previous impact the tail oscillations are even stronger, and their cause is a wide spectrum of the exciting pulse (response).

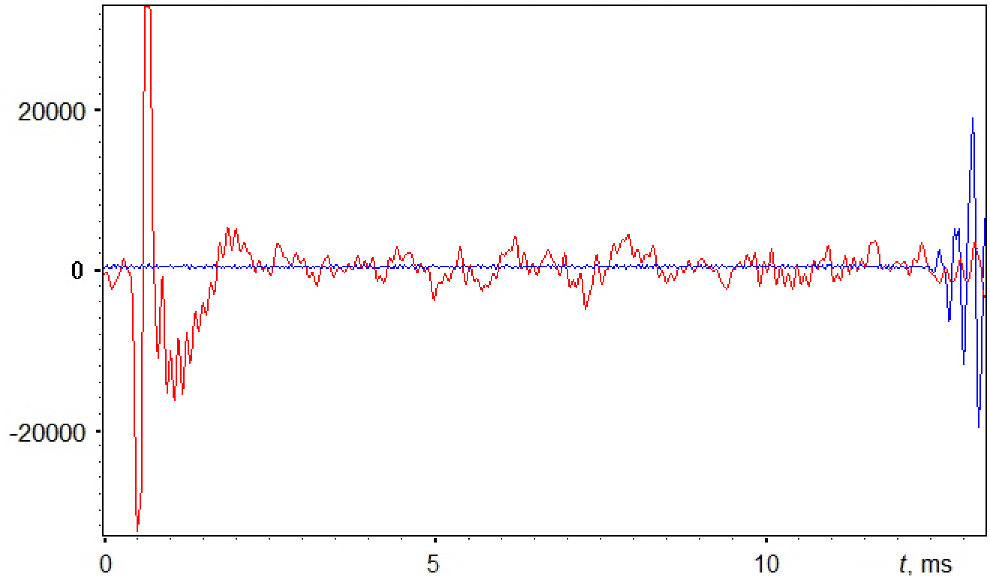

Fig. 19. Oscillogram of the response at a blow by hammer on quartz.

Now, consider an example of the results of our experiments on a plain near the lake in conditions of a wet ground. Fig. 20 shows the spectra of the responses at impacts to a large monolith stone, completely sunk in wet soil.

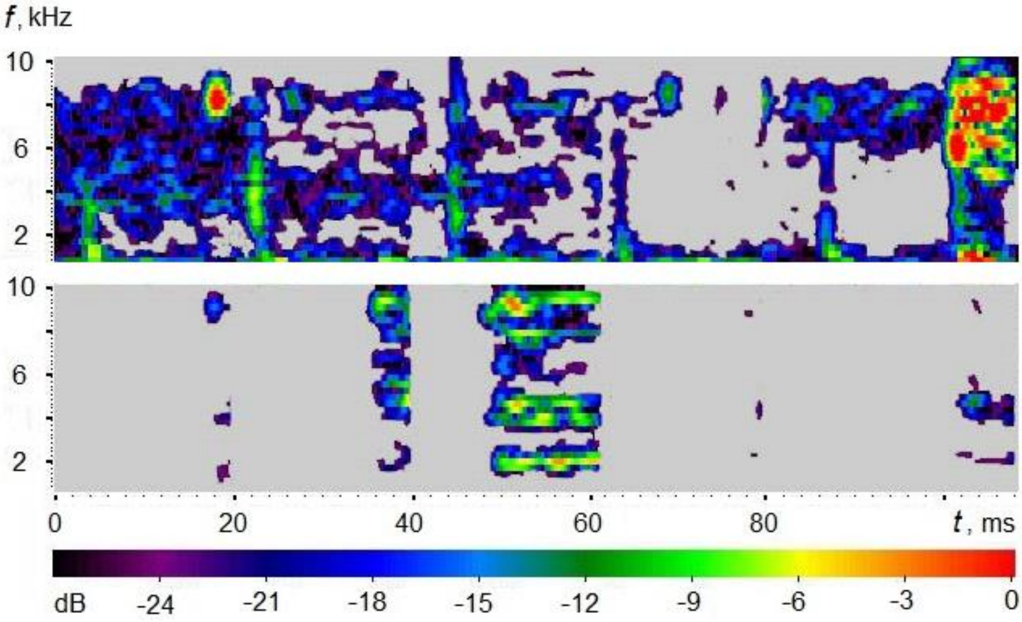

Fig. 20. The electrical and seismic responses observed in the experiments on a plain near large lake.

It should be noted that no noticeable responses were observed from hammer blows during registration. As one can see in Fig. 20, the responses are observed at a stone was thrown off (the 1st spectrum fragment in Fig. 20, time 0–20 ms), at a hammer blow on the granite sample mounted on the surface of recessed stone (the 2nd fragment, time 20–40 ms), at hammer blow on a stone being thrown off (the 3rd fragment, time 40–60 ms, the stone is on the ground close to the antenna, when the stone was in the moss near the main monolith, the responses were not clearly seen) and at impacts on the recessed stone with near-located quartz (the 4th and 5th fragments, time more than 60 ms).

The main conclusion of these experiments is the presence of a shielding effect from wet soil. Therefore, at least at weak seismic impacts, the observation of responses from ore formations under a layer of wet soils in the absence of the ore bodies going to the surface is problematic. Also, a distinctive feature of fragments 2 (granite) and 4, 5 (quartz excited by a seismic wave, without direct impacts) in Fig. 20 is the presence of responses at frequencies above 6 kHz. This confirms the conclusion made in the description of previous field experiments with quartz.

In addition, since we did not receive responses from hammer blows to a recessed stone, as in other experiments, and a response was observed at throw off of the stone, in general we observe responses from both the stone that impacts and the stone to which the blow was. Therefore, in such experiments there is interference of signals. This can explain the appearance of several maxima in the high-frequency range (in addition to previously made assumptions). Note that the multiplicity of maxima also occurred in previous experiments with hammer blows (see Figs. 7 and 8). It is clear that the noted effect complicates the interpretation of experiments with two stones.

Note, that the similar series of experiments (using the hammer and stones both with and without the quartz samples) were carried out also on top of the Marchekansky hill (near Magadan) where the conditions differ essentially from ones in previous experiments. In the results obtained in these experiments, there were no significant fundamental differences from the results of experiments performed in other places. The responses were also clearly observed in this case, that once again confirms the objective nature of the results obtained in previous field experiments.

5. Discussion and Conclusion

A common feature of field and laboratory research is the observation of the low-frequency and high-frequency response components. But in laboratory studies, a modal spectrum structure at frequencies below 5 kHz was not observed, and the high-frequency part was completely determined by the frequency characteristics of the receiver filters (see Part I of the paper). In field experiments, maxima at frequencies of 3–4 kHz were observed. This may be explained by significantly different sizes of the samples. If in laboratory experiments the sizes of the samples did not exceed 15–20 cm, then in the field ones they reached several meters, and the zone of penetration of the seismic wave, which can cause the piezoelectric effect, was 9–17 m.

In laboratory experiments, an increase of the response energy with increasing exposure intensity was observed. At the same time, there was a large scatter in the energy characteristics of the responses under the same initial conditions. Significant dispersion of responses was also observed in field experiments during shock exposure, but on average there was a tendency to proportionality of the effective amplitudes of the electrical and recorded at a distance from the sample seismic pulses. This dispersion was primarily due to the loss of part of the impact energy for the destruction of the samples.

In field experiments, the destruction was observed visually and led to a decrease of the response energy. In the laboratory experiments, the micro-fractures took place that were not visually identifiable. Consequently, macro- and micro-destructions of the sample in the low-frequency range give a significantly weak electrical response than the manifestations of the piezoelectric effect, but the situation can radically change for signals registered by the radio-impulse method (RIM), that are associated precisely with micro-destruction [7].

Summarizing the results of the conducted field experiments and their interpretation presented above, we can conclude the following:

1. The mechanisms of excitation of seismic emission (for various sources) and the generation of the EM response at propagation of seismic wave through a mechanical system, in particular rocks, are considered.
2. As an intermediate stage between laboratory research and the registration of EM responses at industrial explosions, the field experiments were conducted on real geological rocks, and we would like to note the following main results obtained by us:

a) the fact of generation of the EM responses at impacts on various widespread quartz-containing rocks was confirmed; it has been established that the source of the EM emission of the rock in the ELF-VLF range are the excited by seismic wave inclusions of a crystalline piezoelectric;

b) the existence of low and high-frequency parts of the response in the lower part of the VLF range of EM emission generated by impact was detected;

c) the arising of modal structures in the high-frequency responses at impact to rocks in real conditions was detected;

d) the proportionality of the piezoelectric response to seismic one is shown;

e) an increase of the response amplitude due to the presence of an additional massive piezoelectric excited by means of a seismic wave is shown;

f) no noticeable role of the structural destruction of the rock samples in the generation of responses was found, that gives a chance to their detection not only under hard impact (mechanical shocks, explosions), but also during natural seismic processes; that opens the perspectives for using the methods of prediction of seismic phenomena using the EM precursors of the earthquakes;

g) the variations in responses parameters observed in experiments at weak impacts has a logical explanation, taking into account the presence of microdestructions in the samples, that increases the chances of the RIM signals detecting during natural seismic impacts.

In conclusion, some words about the perspectives of further investigations.

In this part of the paper we have considered the responses of the rock samples in the ELF-VLF frequency range that was used in the piezoelectric method (PEM) [1]. It would be interesting to establish a relationship between the PEM and RIM emissions which are also observed at piezoelectric effect [8]. In particular, it is necessary to find out whether RIM signals are always accompanied by PEM signals and whether the latter have special spectral characteristics. It is also necessary to find out which RIM emissions accompanies the piezoelectric effect in widespread rocks. In the framework of these works, a conclusion about the existence of a relationship between the spectral-temporal characteristics of signals in both methods should be made and, if such relationship will be established, to determine its characteristics. And, finally, on the basis of special experiments on the strong seismic effects during industrial explosions, it is necessary to find out the dependence of the PEM and RIM responses on the strength of the seismic effect, that should clarify the possibility of detection of signals which are generated by natural seismic events, for example, of that which were investigated theoretically and numerically in [9-11].

A detailed description of the results obtained when studying the structure of EM emission caused by strong impacts at powerful industrial explosions will be presented in the next part of the work.

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